

## REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE		3. REPORT TYPE AND DATES COVERED Final 1 Jun 86 - 31 Aug 90	
4. TITLE AND SUBTITLE Integrated Semiconudctor Modulators				5. FUNDING NUMBERS  DAAL03-86-K-0089	
6. AUTHOR(S)  Thomas A. DeTemple					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Illinois Urbana, IL 61801				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211				10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 23383.3-PH	
11. SUPPLEMENTARY NOTES The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.					
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Studies have shown that impurity induced layer disordering can be used to fabricate buried channel optical waveguides from the same heterostructure as is used for lasers and the routing properties of these waveguides are exceeded only by those fabricated by non-planar techniques. The importance of these is that of providing an "existence-proof" for this technology for other than straight waveguides. It has been demonstrated that, by using vacancy induced disordering, the band gap can be selectively increased thus rendering a heterostructure transparent to radiation at it's native band gap without any loss in waveguide routing ability. This provides a means for integrating lasers, amplifiers, modulators, detectors and passive waveguides from the same wafer without severe band edge attenuation. It has also been demonstrated that a single quantum well graded barrier laser heterostructure has a significant electroabsorption tail which can be used for a modulator or detector. <i>Keywords:</i>					
14. SUBJECT TERMS Semiconductor Modulators; Optics; Aluminum Gallium Arsenide Heterostructures; Optical Wavequides; Lasers; Heterostructures.				15. NUMBER OF PAGES	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		

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FINAL REPORT

(FIFTY COPIES REQUIRED)

1. ARO PROPOSAL NUMBER: 23383-PH
2. PERIOD COVERED BY REPORT: 1 July 1986-August 31 1990
3. TITLE OF PROPOSAL: Integrated Semiconductor Modulators
4. CONTRACT OR GRANT NUMBER: DAAL 03-86-K-0089
5. NAME OF INSTITUTION: University of Illinois Urbana/Champaign
6. AUTHOR(S) OF REPORT: T.A. DeTemple (217) 333-3094
7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:
  1. F. Julien, P.D. Swanson, M.A. Emanuel, D.G. Deppe, T.A. DeTemple, J.J. Coleman and N. Holonyak, Jr., "Impurity Induced Disorder delineated Optical Waveguides in GaAs-Al Ga<sub>1-x</sub>As Superlattices", Appl. Phys. Lett., 50, 866-869 (1987).
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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD;

T.A. DeTemple (PI)

P. D. Swanson, Ph. D. (1989) in Electrical and Computer Engineering

K. Lee, Ph. D. candidate, withdrew because of illness

C. Herzinger, Ph. D. candidate

BRIEF OUTLINE OF RESEARCH FINDINGS

This research was in the area of semiconductor integrated optics and focussed on electroabsorption properties of MOCVD grown AlGaAs heterostructures. Indirectly, the research was seeking to<sup>1-x</sup>determine if a universal heterostructure existed which could be used for multiple device applications along with a compatible planar, optically self-aligned fabrication technique.

At the time this research was initiated, there was one fabrication technique, impurity induced layer disordering, which had great promise as a base processing technology but was unproven except for the fabrication of lasers which are simple straight waveguides. Therefore a considerable part of the initial period of this grant was directed at patterning and understanding the routing behavior of abrupt-like and s-like bends primarily to understand the nature and quality of the guides. Our results are summarized below with references indicating the relevant manuscript entry.

- We have shown that impurity induced layer disordering can be used to fabricate buried channel optical waveguides from the same heterostructure as is used for lasers<sup>1,2,3,4,6,7</sup> and the routing properties of these waveguides are exceeded only by those fabricated by non-planar techniques. The importance of these is that of providing an 'existence-proof' for this technology for other than straight waveguides.
- We have demonstrated that by using vacancy induced disordering, the band gap can be selectively increased thus rendering a heterostructure transparent to radiation at its native band gap without any loss in waveguide routing ability<sup>8</sup>. This provides a means for integrating lasers, amplifiers, modulators, detectors and passive waveguides from the same wafer without severe band edge attenuation.

The second half of the funding period was directed at electroabsorption studies of single quantum well laser geometries.

- We have demonstrated that a single quantum well graded barrier laser heterostructure has a significant electroabsorption tail which can be used for a modulator or detector. We have shown that this absorption is not due to the familiar quantum confined Stark effect but rather is a new effect which we called the quantum unconfined Stark effect<sup>5,6</sup>. Using controlled vacancy induced disordering, one

may slightly blue shift the gap of such a modulator thus providing a small band edge loss under forward bias conditions and a much higher loss under reverse bias conditions. This type of modulator could be used for amplitude or phase modulation or as an optical tap all depending on the degree of blue shifting and modulator length.

We are currently investigating the first integrated laser-electroabsorption modulator for which the latter has been blue shifted by vacancy induced disordering. Our initial findings indicate that the wavelength of the laser is electronically tunable over some 20 to 30 nm by the modulator. Our hope is to be able to demonstrate continuous frequency tuning and small linewidths.

From our perspective, the primary bottleneck in integrating a laser onto a chip with passive waveguides now appears to be the interior laser mirror/waveguide coupling structure. The vertical diffraction angle of these lasers is about  $50^\circ$  so by using, for example, a simple etched interior facet mirror serious insertion loss and feedback effects would occur. To solve some of these will require the development of an equivalent interior mirror for which the mode does not exit into air, one example of which is a distributed feedback mirror which is now feasible given the blue shift techniques. There are other possibilities which are not as demanding of the lithography and which are currently being explored at Illinois and other institutions.

There are two other important issues which are specific to the laser heterostructure investigated to date; linear loss and modal coupling efficiencies. Because our samples were doped as lasers, free carrier loss should be present. A review of the literature has revealed that there is no reliable measurement of this loss in these structures, only estimates which ranged from 2 to  $10 \text{ cm}^{-1}$ . For small chips with a few mm path length, these losses are not important. For longer path lengths which are still available in small chips, the loss becomes significant but must be measured against the very high gain,  $>100 \text{ cm}^{-1}$ , available by biasing some region to be an amplifier. At this time it is not known how much this loss can be lowered by lowering the doping without degrading the laser performance.

The vertical size of the mode within the semiconductor is only about  $1/4 \text{ } \mu\text{m}$ . This presents difficulties in focussing and matching externally since one can only focus to about  $1 \text{ } \mu\text{m}$  in diameter. Since this mode size is specific to an optimized single quantum well GRINSCH structure, one may anticipate that coupling losses caused by modal mismatch may be improved. Again, this may result in laser degradation but that has to be taken within the context of a set of desired performance requirements for the chip. Our present feeling is that the laser characteristics are the least important since there is so much flexibility demonstrated in laser geometries. The most important is always application specific and remains to be defined on a case-by-case basis. Given the demonstration to date on the number of devices which can be fabricated from this one heterostructure by this processing technology and the flexibility in tailoring electrical, optical and electro-optical properties inherent in the growth technologies, it is easy to be optimistic and enthusiastic about the pursuit of a universal heterostructure for which the presents laser structure serves as a useful first approximation.

Although our studies have concentrated on Al Ga<sub>1-x</sub>As based systems, impurity induced disordering is known to exist in  $\text{In}^{1-x}(\text{Al Ga}_x)_{1-y}\text{P/GaAs}$ , strained In Ga<sub>1-x</sub>As on GaAs and in  $\text{In}^{1-x}(\text{Al Ga}_x)_{1-y}\text{As}$  on  $\text{InP}^{1-x,1-y}$ . This suggests that our basic universal heterostructure, when realized, could be implemented in other technologically important material systems.

# PROCEEDINGS REPRINT

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## Digital Optical Computing II

17-19 January 1990  
Los Angeles, California

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Volume 1215

## Disorder delineated semiconductor waveguides

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### ABSTRACT

The routing ability of waveguide structures patterned by impurity induced layer disordering of AlGaAs superlattice and graded barrier heterostructures is discussed along with issues associated with the integration of multiple optical devices into the waveguides.

### 1. INTRODUCTION

The design and fabrication of semiconductor optoelectronic integrated circuits (OEIC) pose major challenges because of the seemingly conflicting individual material requirements for electronic and optical devices. At present, there is no obvious resolution of these except those involving complicated etching along with crystal regrowths. Ideally what one would like would be a universal heterostructure wafer and a planar, optically self aligned processing technology such that parts of the wafer could be used for electronic and optical devices, parts for static optical routing and other parts for dynamic routing. The planarity requirement stems from the difficulties in metallizing over topologically high portions of a wafer and the desire to avoid rib waveguides which have demanding depth requirements. The optically self aligned requirement stems from the very small dimensions associated with semiconductor waveguides,  $\approx 1 \mu\text{m}$ , and the obvious inability to 'tune' something into alignment. The universal wafer requirement stems simply from the desire to not employ etching and crystal regrowths. Recognizing these desirable requirements is easy but satisfying them is an entirely different matter.

This paper addresses the properties of guiding structures patterned by one processing method which, in principle, has the characteristics just outlined. The effect, impurity induced layer disordering (IILD), was discovered in 1981<sup>1</sup> and is an impurity driven instability present in a III-V heterostructure. At sufficiently high temperatures, a heterostructure will thermally intermix or disorder due to self-diffusion.<sup>2</sup> At lower temperatures, particularly those associated with impurity incorporation and for which thermal disordering may be negligible, certain materials disorder under the presence of the impurities, that is the impurities enhance self-diffusion. The effect is most pronounced in thin heterostructures and invariably results in a new material, which is the compositional average of the original heterostructure and which has a larger band gap and hence lower index of refraction by Moss's rule. The effect is known to exist in at least three material systems which maintain a lattice match after disordering and are summarized below and reviewed elsewhere.<sup>3</sup>

System	$\lambda \mu\text{m}$	Impurity/T/time	Thermal D.O.
$\text{In}_y[\text{Al}_x\text{Ga}_{1-x}]_{1-y}\text{P:GaAs}$	0.6	Zn, 600 °C, hr	850 °C, day
$\text{Al}_x\text{Ga}_{1-x}\text{As:GaAs}$	0.9	Zn, 600 °C, min Si, 800 °C, day	850 °C, day
$\text{In}_y[\text{Al}_x\text{Ga}_{1-x}]_{1-y}\text{As:InP}$	1.5	Zn, 550 °C, hr	750 °C, hr

Since the incorporation of impurities is controllable by masks, the effect can be used to fabricate optically self aligned guiding structures without topographic modification of the surface and it is the passive properties of such structures which are of concern here since it has been demonstrated earlier that the effect can be used to fabricate high quality AlGaAs lasers.<sup>4</sup>

In outline, the next section outlines the characteristics of some simple routing structures fabricated by IILD. This is followed by a section which addresses some of the problems and potential solutions present when multiple devices are to be integrated.

## 2. ROUTING EXPERIMENTS

Although AlGaAs lasers were patterned very early by IILD, little could be deduced from their behavior on the quality of passive routing structures made by the same technique. Motivated by our initial qualitative observations on simple berds<sup>5</sup>, we have investigated a number of routing geometries primarily from a standpoint which might be called a 'proof-of-concept'. The standard structure investigated contained of a 1  $\mu\text{m}$  thick superlattice comprised of 50 nm AlAs, 50 nm GaAs bounded top and bottom by 1  $\mu\text{m}$  of  $\text{Al}_{0.5}\text{Ga}_{0.5}\text{As}$ . The central portion of the superlattice also contained an isolated 10 nm GaAs<sup>0.5</sup> quantum well which was used to synthesize an approximate laser-like structure. The structure, grown by metal organic chemical vapor deposition, was doped to form a p-i-n diode. This structure was adopted because of its conceptual simplicity (the lateral disordered region would have the same compositional average as the upper and lower confining layers making this a simple buried channel waveguide surrounded by a uniform material) and because of the expected mode sizes based on the index of refraction of the superlattice.<sup>6</sup> Figure 1 shows an SEM image of a cleaved and etched facet of one such disordered sample. Clearly seen are the diffusion fronts which undercut the masks seen as the dark bars on top, and the trapezoidal shaped regions which contain the native superlattice or waveguide core. The smallest waveguides in this sample are approximately 1  $\mu\text{m}$  by 1.5  $\mu\text{m}$  in size and result in a measured near field mode diameter of approximately 1  $\mu\text{m}$ , limited by the resolution of the imaging optics at this wavelength,  $\approx 860$  nm.

To test these guides for loss in a routing geometry, four patterns were investigated: abrupt bends, modified abrupt bends in a pattern due to Shiina<sup>7</sup>, and parallel offset guides connected by either two constant radius sections or raised cosine sections. Measurements were taken with a tunable laser, Stryl 9m dye or Ti:sapphire, which was endfire coupled into the guiding structures using a microscope objective. The exiting mode was imaged through a 1000X microscope and detected either with a silicon CCD camera or with a silicon photodiode connected to a lock-in amplifier. The excess loss of a particular routing geometry was deduced by using the transmission of straight waveguides patterned on the sample wafer as norms. In the data to be presented, all samples were patterned using Zn diffusion from a ZnAs source in a sealed ampule and measured near 860 nm with TE polarized light.

Figure 2 shows the measured excess loss for the two bending geometries.<sup>9</sup> The abrupt bend data can be fit with a simple loss model based on Gaussian coupling between two inclined guides.<sup>10</sup> The data are fit with guide parameters which are consistent with a lateral index of refraction difference of about 1%. Of more interest are the angles corresponding to 3 dB loss which are 3° and 7° for the abrupt and Shiina bends. While not numerically large, these values must be compared with those in  $\text{LiNbO}_3$  which are typically 1°.<sup>10</sup>

Figure 3 shows the measured excess loss for the raised cosine pattern versus transition length  $t$  for multimode guides ( $1 \times 8 \mu\text{m}$ ) and near single mode guides ( $1 \times 1.5 \mu\text{m}$ ).<sup>11</sup> The expected deleterious effect of multimode guides is confirmed in these data and in the data of other IILD structures.<sup>12</sup> The near single mode data are

consistent with a lateral index difference of 1% determined by model fitting.<sup>13</sup> For a large number of samples, the transition distance for 3 dB loss is found to be  $\approx 300 \mu\text{m}$  for this heterostructure disordered with Zn.

Although the data are fit with a lateral index difference of 1%, a value similar to that deduced by other measurements<sup>14</sup>, we feel that this is probably not the true index difference for the following reasons. The compositional dependence of the bulk index of refraction of AlGaAs is not linear with composition  $x$ .<sup>15</sup> Therefore, the index difference between a fully disordered material and the native structure can be as large as 0.7%. The native structure in this case is a superlattice which is known to have a higher index of refraction than the geometrical average of the structure by some 1% leading to a lateral index difference closer to 2%.<sup>6, 16</sup> The Zn concentration adjacent to the waveguide wall is thought to be in the range of  $10^{19} / \text{cm}^3$  which in and of itself should result in an index difference of 1%<sup>15</sup> for a net lateral index difference of 3%. However at this concentration, there can be a substantial free carrier loss<sup>17</sup>,  $\approx 100 \text{ cm}^{-1}$ , so that when the mode shifts into the lateral cladding layer in a bend one has free carrier as well as radiative losses which mask the true radiative dominated behavior. A further complication is that only partial disordering takes place with Zn which means that the lateral index difference is due in part to doping and in part to incomplete intermixing.<sup>3</sup> Other impurity species are available for which the free carrier loss should be less and which may have a higher degree of intermixing.<sup>3, 18</sup> The degree of routing of guiding structures patterned with these have not been fully investigated yet.

There is only limited device use for superlattices of the kind investigated. Therefore we have studied s-bend structures patterned in a single quantum well graded barrier heterostructure wafer (SQW-GRIN-SCH).<sup>19</sup> This structure is conceptually different than the superlattice structure because the lateral index difference is due to disordering of essentially a bulk-like core. The GRIN-SCH structure studied was comprised of a 10 nm GaAs quantum well centered in a parabolically graded core of full width  $2d=0.25 \mu\text{m}$  and graded from 20% Al adjacent to the well to 85% Al at the edge of the grade and throughout the approximately  $1 \mu\text{m}$  thick upper and lower confining (cladding) layers. The structure was doped in a manner known to yield good laser behavior.<sup>19</sup>

As a simple estimate, we have applied a standard thermal diffusion model to the GRIN-SCH structure and then used the effective index approach to determine the equivalent lateral waveguide V parameter. Figure 4 shows the calculated Ga distribution for various diffusion times obtained by ignoring the quantum well. The native graded region supports a fundamental Kummer-Gauss mode with a vertical waveguide V parameter of about 1.4.<sup>20</sup> As diffusion progresses, the core increases in size and the index difference is reduced. The modal properties for the thermally disordered case were found from a fourth order Runge-Kutta solution of the scalar TE-wave equation<sup>20</sup> and converted to a lateral V parameter by assuming an abrupt boundary between the native and disordered region and a  $1 \mu\text{m}$  wide core. The results of this model situation are shown in Fig. 5. One sees from Figs. 4 and 5 that a relatively small Ga redistribution is needed to establish a good lateral guide: for example,  $\xi=0.5$  corresponds to a single mode lateral guide with a 1% effective index difference.

Figure 6 shows the s-bend loss for the GRIN-SCH patterned with Zn IILD. SIMS data reveal that the disordered core has slightly increased in size and is roughly approximated by the  $\xi=0.5$  case in Fig. 4. As in the case of the superlattice, there may be an additional contribution to the lateral index difference due to doping. Data on the same structure patterned by Si disordering<sup>3</sup> also indicate an approximate 1% lateral index difference and an approximate doubling of the width of the core region.

### 3. INTEGRATION ISSUES

Although these data are indicative of the quality of the guides, there are still many unknowns and potential problems which need to be addressed. One issue which must be faced with the use of a common wafer for passive and active devices is the linear loss, particularly that due to absorption near the fundamental edge, and a second issue is associated with the interior laser mirror/waveguide coupler. The linear waveguide loss in the superlattice structure has been estimated by the cutback technique to be in the range of  $2\text{--}10\text{ cm}^{-1}$  for light near the band edge. Others have deduced lower and higher losses for light near and far from the band edge using different disordering impurities and different heterostructure geometries.<sup>14, 18, 21, 22</sup> The non-edge loss may be associated with the wall shape, the abruptness of the transition between the native and disordered region<sup>3</sup>, defects in the disordered region<sup>23</sup>, and free carrier absorption in both the native and disordered regions. The role of each of these is not well understood.

It is well known that the emission wavelength of quantum well laser is close to the two dimensional band edge and would be in a spectral region of strong absorption in an unbiased waveguide. Even with the presence of strong carrier induced red shifts, it is not likely that current can be used to red shift the emission line far enough from the edge to eliminate self absorption.<sup>24</sup> There are three other possibilities for reducing the band edge loss: bias the guides to transparency, process the guides such that a blue shift of the band edge occurs, or design the wells for transparency.

Biasing the guides to transparency is not impractical because of the small lateral dimensions. Taking a threshold current density of  $100\text{ A/cm}^2$  as an example, a  $2\text{ }\mu\text{m}$  wide waveguide requires some 20 mA per cm of length for gain and somewhat less for transparency. We do not envision cm long paths in OEICs but rather mm long paths each of which would consume only mW's of power for waveguide transparency/gain.

The process-to-transparency approach involves selective disordering. It has previously been demonstrated that by varying the degree of undercutting seen in Fig. 1, a slight disordering of a twin quantum well structure could be achieved which increased the gap sufficiently to allow the integration of a passive waveguide into an active cavity.<sup>25</sup> However it is not known what compromises in routing ability occur because of this. In an impurity free process, vacancy disordering was used to modify the shape of quantum wells which increased the gap by an astounding 30 nm while still preserving excitonic features.<sup>26, 27</sup> This was achieved with a short, high temperature anneal. The use of this in the planar geometry would require a selected introduction of vacancies which is made easier with the use of solid sources. Shifts of the same magnitude can be achieved using thermal disordering<sup>28</sup> but would require either local thermal shielding or locally selective heating to be of use in a planar geometry.

Designing the wells for transparency is accomplished by having both red and blue shifts and is a new and intriguing idea recently proposed for SEED devices.<sup>29</sup> This approach employs coupled asymmetric quantum wells which may have both shifts depending on the sign and direction of the field. What is potentially appealing about this is to be able to bias to transparency without much current flow in contrast to the gain scenario. The viability of these approaches all remain to be investigated in detail.

### 4. SUMMARY

The experimental data on the routing behavior of waveguides patterned by IILD suggest a future role as a base processing technology for OEIC's. The SQW-GBH serves as a case study in the use one wafer for multiple device roles, a laser<sup>19</sup>, passive

waveguide, phase modulator<sup>28</sup>, electroabsorption modulator<sup>30, 31</sup> and detector, and define some of the problems which remain to be addressed. In addition to linear loss issues, the fabrication of an interior mirror which provides laser feedback and low loss coupling into an exterior guiding structure remain as open challenges.

## 5. ACKNOWLEDGMENTS

It is a pleasure to acknowledge many useful discussions with D. Deppe, F. Julien, J. Major, N. Holonyak, Jr., and I.A. White. This research was supported in part by the NSF sponsored Engineering Research Center for Compound Semiconductor Microelectronics ECD 89-43166, the U.S. Army Research Office: Durham and the University of Illinois Industrial Affiliates Program.

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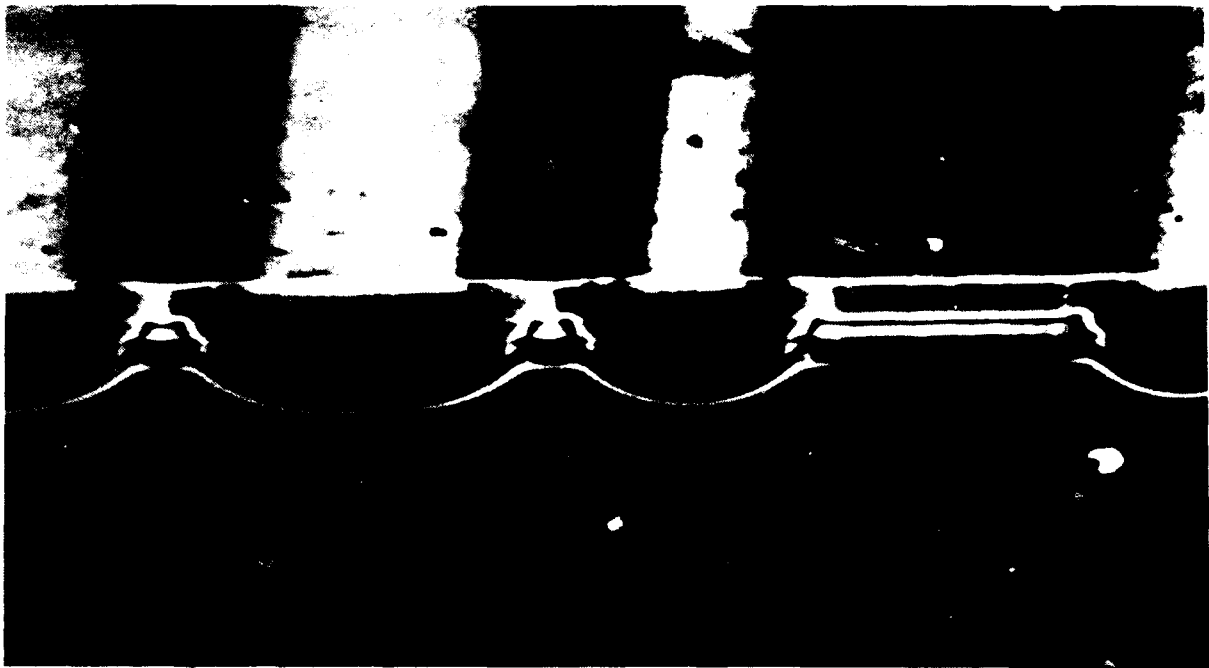


Fig. 1. Scanning electron microscope image of the top and stained facet of a disordered superlattice. The native structure is bounded within the trapezoidal regions.

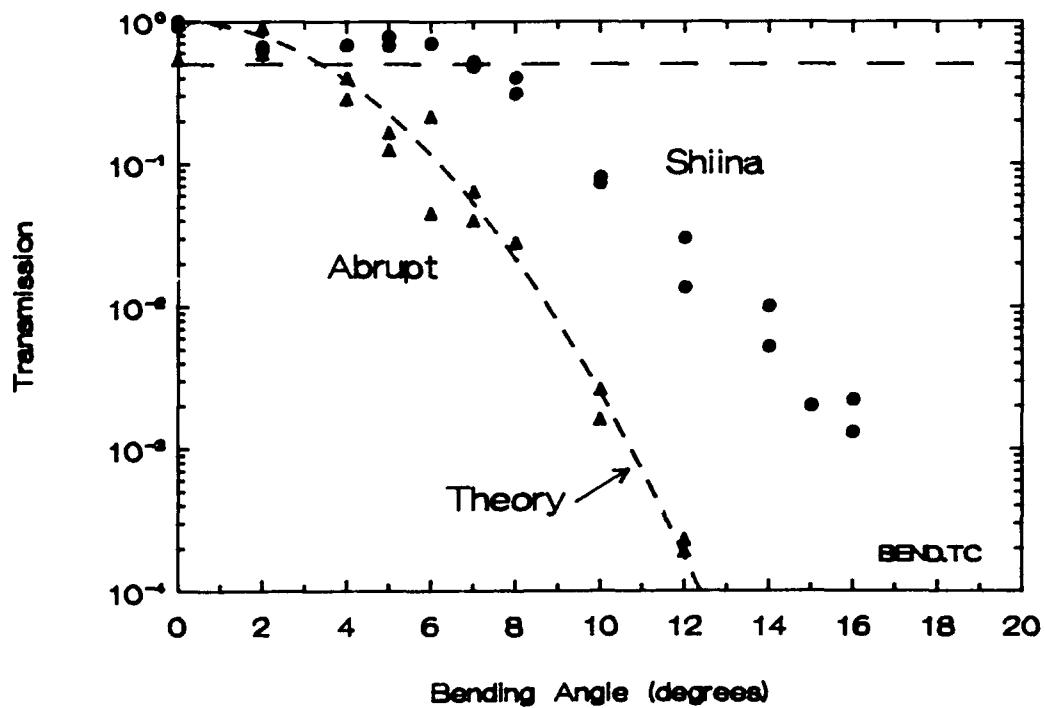


Fig. 2. Transmission through abrupt and Shiina bends patterned in a Zn disordered superlattice.

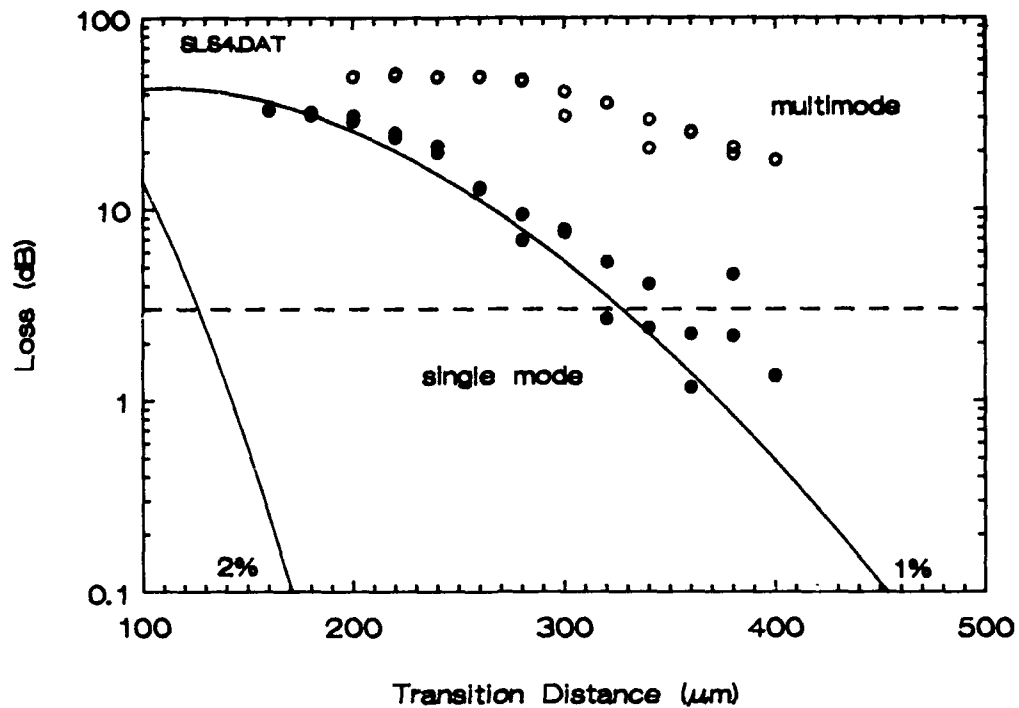


Fig. 3. Transmission through a raised cosine s-bend patterned in a Zn disordered superlattice. The s-bend contained two parallel guides offset by 100  $\mu\text{m}$ .

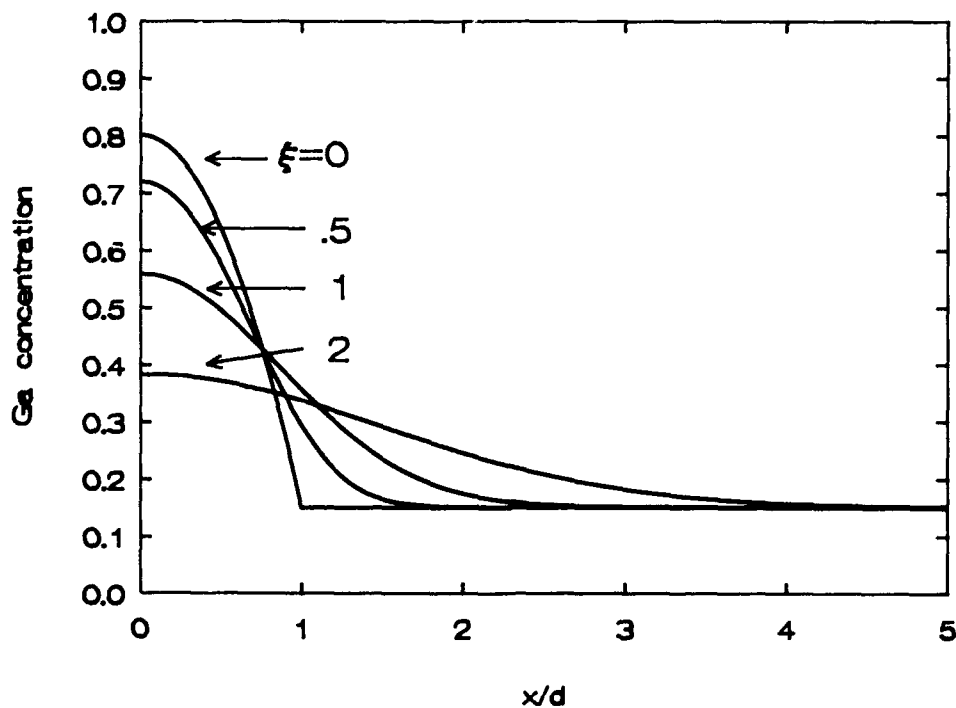


Fig. 4. Calculated thermal disordered profile of a SQW-GBH structure versus time. The variable is  $\xi = (4Dt)^{1/2}/d$  where  $D$  is the Al-Ga diffusion coefficient.<sup>2</sup>

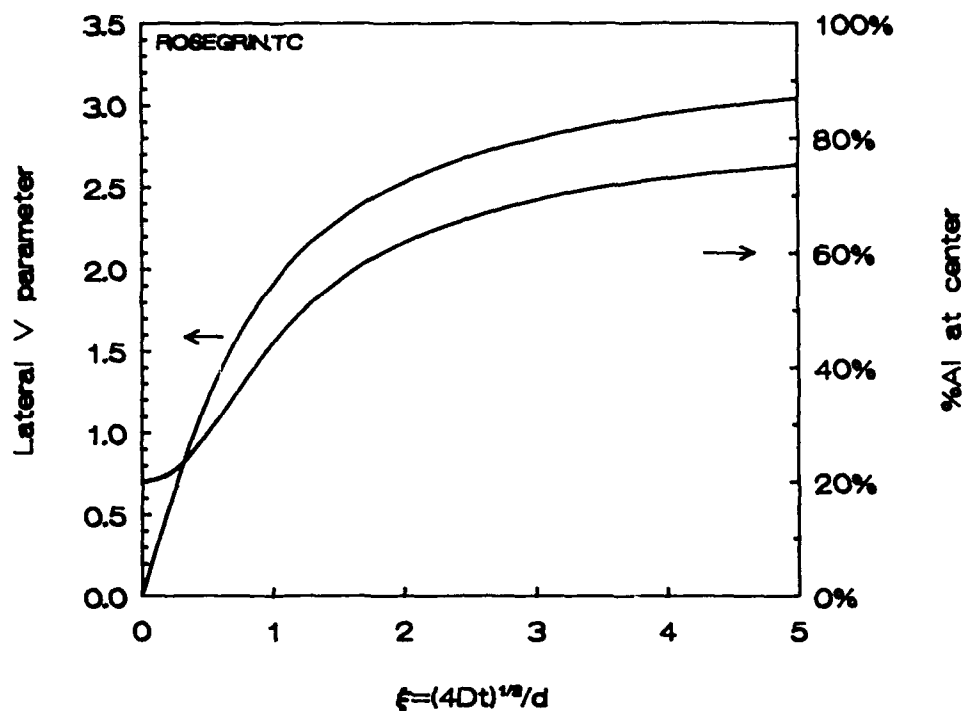


Fig. 5. Calculated lateral waveguide V parameter for the thermally disordered profile of Fig. 4. The lateral waveguide width was taken to be  $1 \mu\text{m}$  and the effective index method was used for TE modes.

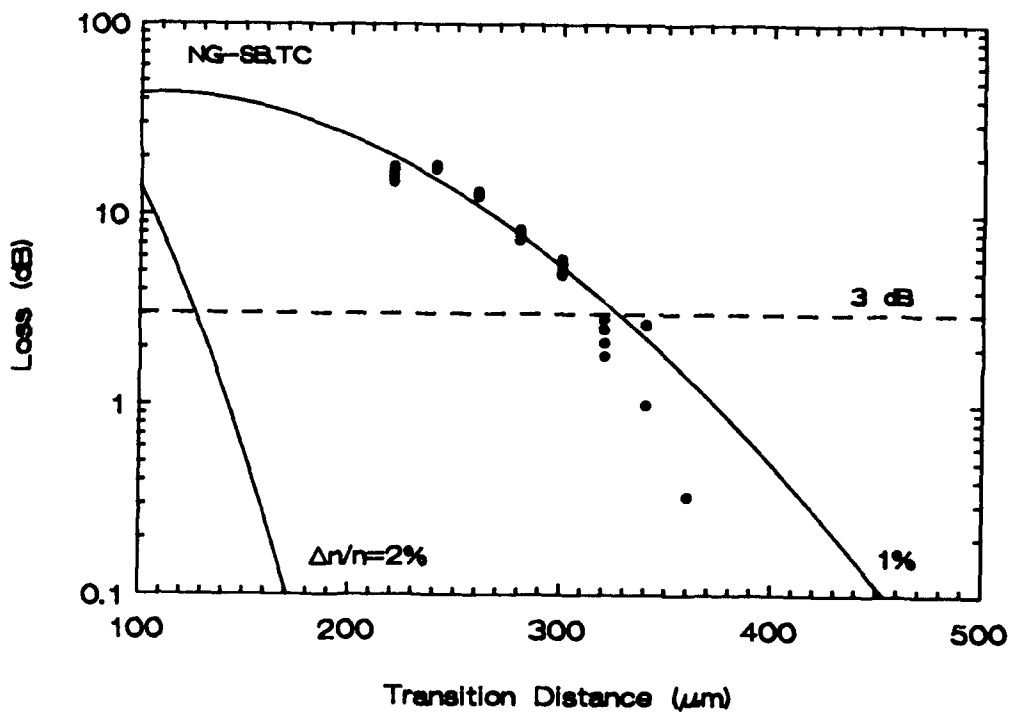


Fig. 6. Transmission through a raised cosine s-bend patterned in a Zn disordered SQW-GBH sample. The s-bend contained two parallel guides offset by  $100 \mu\text{m}$ .